Ampere class linacs: Status report on the BNL cryomodule ☆

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Abstract

A five-cell high current superconducting cavity for the electron cooling project at RHIC has been designed. The 703.75 MHz cavity and cryomodule is under fabrication and nearing completion. The different components of the cryomodule and the status of their fabrication is discussed.

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1. Introduction

Electron cooling is a key component in RHIC II, the next luminosity upgrade to combat intrabeam scattering of ions. Cooling gold beams at 100 GeV/nucleon require an electron beam energy of 54 MeV and a very high average current of about 200 mA. Future projects such as eRHIC (electron-ion collider) push the operational current to ~500 mA at 20 nC bunch charge or higher. A five-cell superconducting cavity and cryomodule as shown in Fig. 1 is under fabrication as a fundamental unit for the linac structure to accelerate the electron beam from 2.5 to 54 MeV [1].

A prototype energy recovery linac (ERL) is under construction at the RHIC facility as a first step towards an ampere class electron cooler. The ERL will act as a test bench to investigate the feasibility of accelerating high current beams and study several beam stability issues in this regime in an energy recovery mode. The ERL will consist of a 703.75 MHz, 2 MeV SRF gun [2] as an injector to the five-cell linac cavity which will accelerate the beam to about 20 MeV. The beam will pass through a recirculating ring and back into the cavity at 180° out of phase to recover the energy and will be extracted into the beam dump. Fig. 2 shows a 3D engineering graphic of the ERL facility in Bldg. 912 at Brookhaven National Lab (BNL). The 50 KW transmitter is in place and work is ongoing on the shielding, interlocks, cryogenics, a.c. power and other engineering aspects of the project. Fig. 3 shows the proposed layout of injector, linac and recirculating ring for the prototype ERL.

2. Cavity

The cavity design is greatly influenced by the operational mode of the linac. Several factors influenced the key parameters of the linac cavity including synchronization with RHIC frequency, higher order mode (HOM) damp-
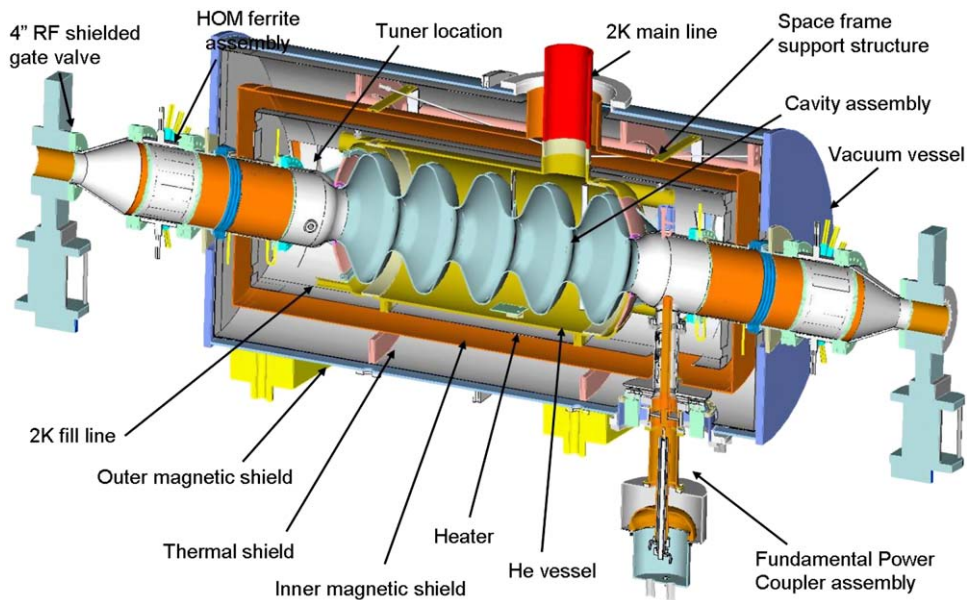

Fig. 1. Cut away view of cryomodule and its components.
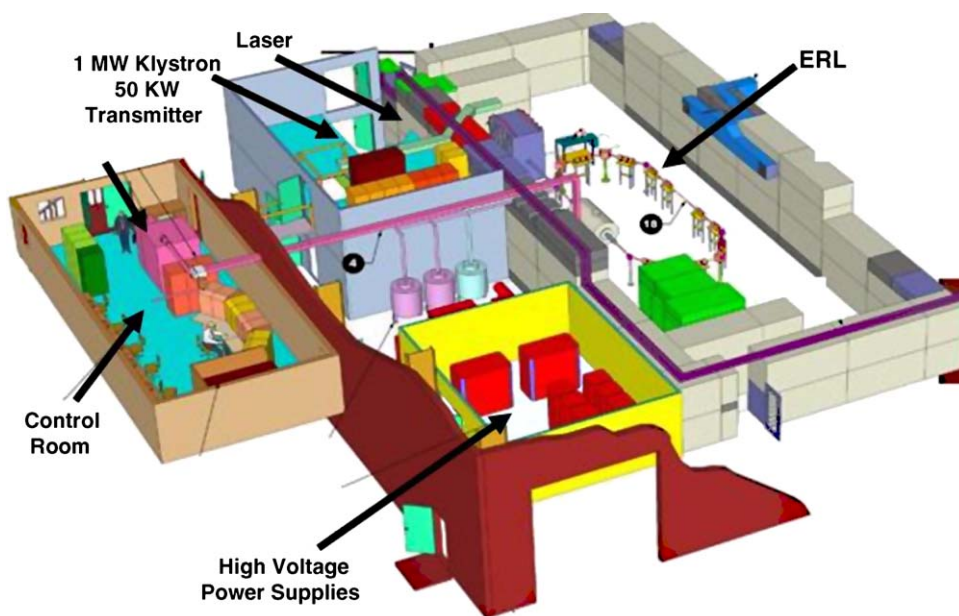

Fig. 2. 3D engineering drawing of ERL facility at BNL including the ERL, control room, power sources, cooling dewars, shielding and other equipment.
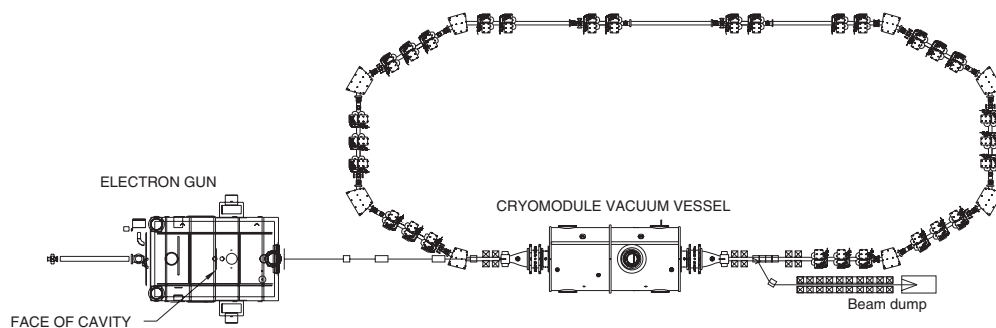

Fig. 3. Layout of the proposed prototype ERL which includes the SRF gun, linac cavity, recirculating linac and the beam dump.
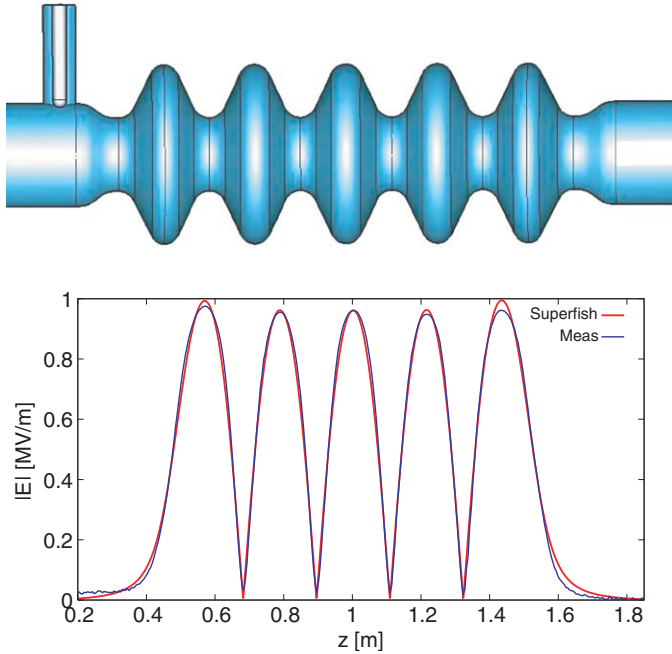
Fig. 4. Graphic of the five-cell cavity and field flatness of the fundamental mode from simulation and a measurement from the copper prototype.

Table 1
Cavity parameters

Frequency	703.75 (MHz)
RHIC harmonic	25
Number of cells	5
Active cavity length	1.52 (m)
Iris diameter	17 (cm)
Beam pipe diameter	24 (cm)
$G(\Omega)$	225
R/Q	403.5 (Ω)
Q BCS @ 2K	4.5×10^{10}
Q_{ext}	3×10^{7}
E_p/E_a	1.97
H_p/E_a	5.78 (mT/MV/m)
Cell to cell coupling	3%
Sensitivity factor ($\frac{N^2}{\beta}$)	833
Field flatness	96.5%
Lorentz detuning coeff.	1.2 (Hz/(MV/m)^2)
Lowest mech. resonance	96 (Hz)
$k_{\parallel}$ ($\sigma_z - 1\,cm$)	1.1 (V/pC)
$k_{\perp}$ ($\sigma_z - 1\,cm$)	3.1 (V/pC/m)
HOM power (10–20 nC)	0.5–2.3 (kW)

ing, and availability of high power RF sources which are described in detail in Ref. [1,3]. The final design of the optimized linac cavity along with the field flatness is shown in Fig. 4. Table 1 shows the RF parameters of the proposed ERL cavity for the electron cooling project.

3. Copper prototypes and testing

Copper (Cu) prototypes play an important role in the investigation of many RF characteristics of SRF cavities. Although, numerical codes have become more accurate and fast in calculating electromagnetic fields, HOM damping with complicating 3D geometries and lossy ferrite materials is still a challenge. Therefore, it becomes imperative to benchmark the simulation results with prototypes for new designs of SRF cavities. They also provide critical engineering experience in manufacturing complicated elliptical structures with strict tolerances. Two copper prototypes were built for testing purposes and results of HOM damping issues are discussed in detail in Ref. [4]. Fig. 5 shows the Cu prototype on a tuning device for frequency and field flatness as well as a beadpull setup to measure field profiles and HOMs.

Two Cu prototypes were built to test a future possibility of integrating them into a superstructure (weakly coupled) to improve the "real-estate" gradient while maintaining the HOM damping comparable to the single cavity. The superstructure also allows the possibility of integrating two cavities in a single cryostat driven by a single power coupler. The transition between the two cavities is under design and the testing will be performed soon. Fig. 6 shows the test setup for the measurements.

4. Niobium fabrication

The Niobium fabrication and tuning of the half cells dumbells were completed in February of 2005. The dumbells and engroups are show in Fig. 7. The electron beam welding of the five-cells and the end groups have also been completed in May 2005 and the final cavity is being prepared for tuning as shown in Fig. 8. The cavity will be tuned to achieve a good field flatness (>96%) across the five cells. An initial target frequency has been calculated for the warm Nb cavity which after chemical treatment, cryostat assembly with all mechanical loads and cooling

Fig. 5. Copper prototype tuning fixture (AES) and beadpull setup for field profile and HOM measurements. Measured field flatness $97 \pm 0.5\%$.

to 2 K will bring the cavity close to the operating frequency of 703.75 MHz.

5. Fundamental power coupler

Due to proximity of the frequency to the SNS cavity (805 MHz), a design choice to adapt the SNS coaxial power coupler to 703.75 MHz was made. The coax-to-waveguide transition assembly was modified to match to 703.75 MHz. Fig. 9 shows a schematic of the fundamental power coupler (FPC) and its corresponding components. The processing of the FPC is anticipated to be performed at Oak Ridge National Lab (ORNL) using the infrastructure developed for the SNS coupler. A collaboration between BNL, Jefferson Lab (JLAB) and ORNL has been setup to implement the conditioning procedure similar to the SNS coupler conditioning. The SNS conditioning system is setup for 805 MHz and issues regarding multipacting because of a conditioning frequency being different from the operating frequency are under investigation. A possibility to condition using the 50 KW amplifier at the BNL facility at 703.75 MHz is also under consideration.

6. Tuner

The large iris aperture lends itself to a steep cavity wall angle and hence an inherently stiff cavity. The Lorentz detuning coefficient was determined to be $1.2 \, \text{Hz}/(\text{MV/m})^2$ and thus eliminates the need of stiffening rings. However, a stiff cavity also poses tuning challenges. A high strength steel alloy frame using a design adapted from the SNS tuner was designed. The tuner components include a high torque stepper motor for coarse tuning and a piezo-electric actuator for fine tuning of the cavity frequency. Fig. 10 shows a schematic of the tuner assembly mounted on the end group and helium vessel. The required tuning parameters of the cavity and design values of the tuner are listed in Tables 2 and 3.

7. Buffer chemical processing

The buffer chemical treatment (BCP) of the cavity is planned to be performed at the SRF facility at JLAB. The complete procedure of the BCP has been identified and discussed in detail in Ref. [5]. The procedure will include an initial heavy etching of 200 μm of the Niobium (Nb) surface followed by baking in vacuum and RF testing at 300 and 2 K. A light BCP may be performed if the Q_0 and accelerating gradient are not satisfactory. A high pressure

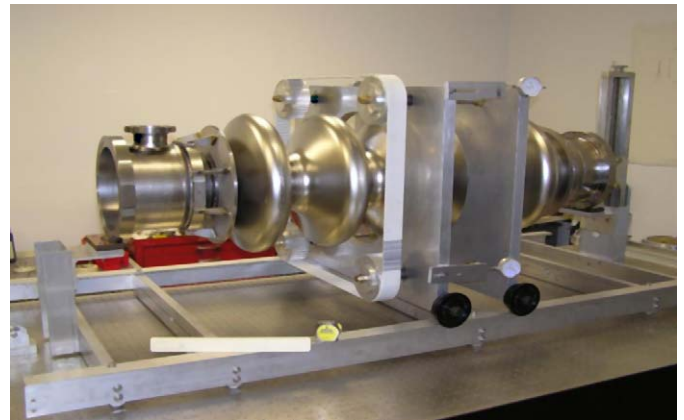Fig. 6. Superstructure setup to measure field profiles and HOM damping.

Fig. 8. Fully electron beam welded Nb cavity in the AES tuning fixture for field flattening and frequency tuning.
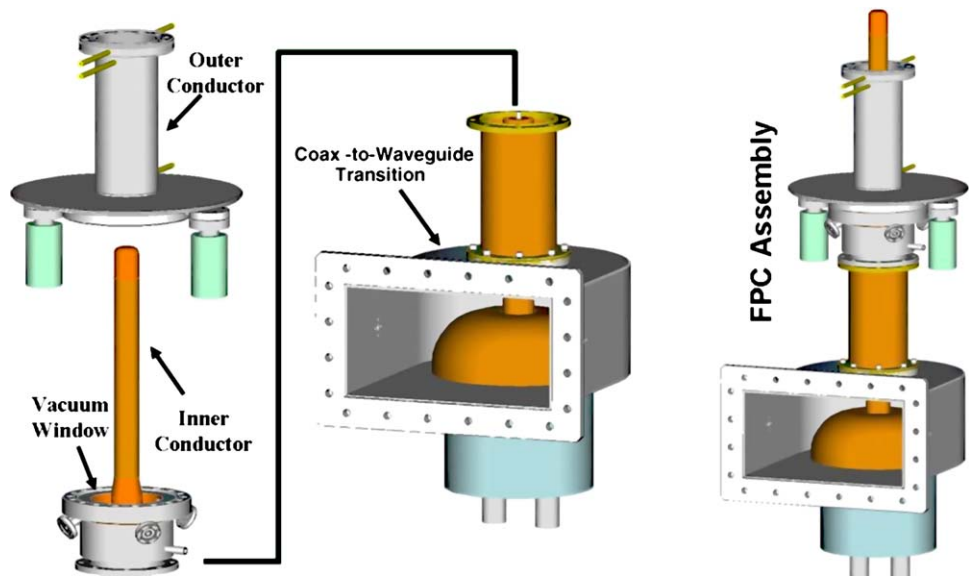

Fig. 7. Nb half cells and engroups.

Fig. 9. Graphic of the fundamental power coupler and its corresponding components adapted to 703.75 MHz from SNS coupler design.
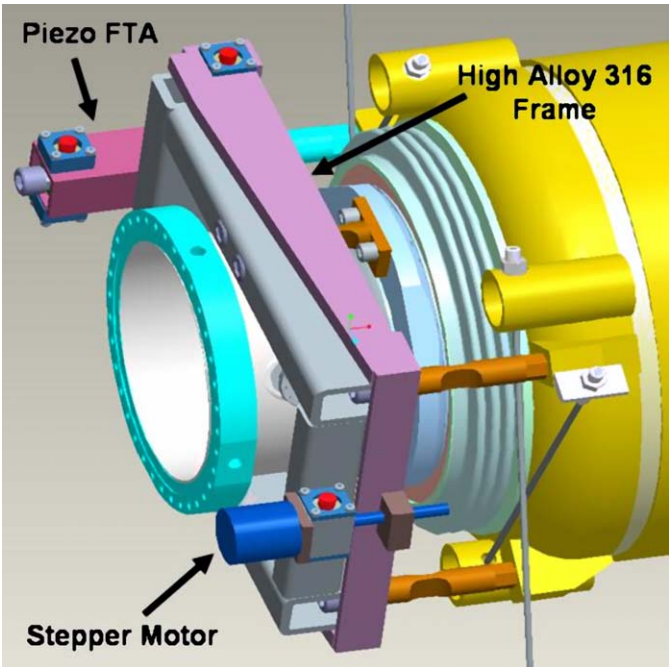

Fig. 10. Graphic of the cavity and helium vessel with the proposed tuner assembly located in the opposite end of the power coupler.

Table 3
Cavity parameters

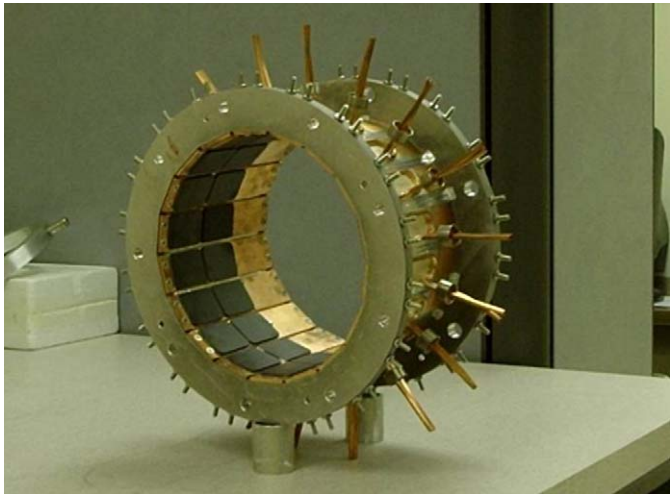| Frequency range	475 KHz	2 KHz
Resolution	1 KHz	25 Hz
Speed	1 s/KHz	<10 μs/Hz
Duty	<8/day	cw

Fig. 11. Prototype ferrite absorbers for HOM damping measurements on the copper model.

water rinse will be performed before the welding and assembly of He vessel and other components. A special system is under fabrication at BNL due to the incompatibility of the cavity in the JLAB water rinse cabinet. Engineering efforts are nearing completion to provide any tooling and equipment that are required specifically for the five-cell cavity to adapt with the existing JLAB infrastructure.

Table 2
Cavity parameters

Tuning range	475 KHz
Tuning coefficient	100 ± 10 Hz/μm
Maximum displacement	4.75 mm
Cavity stiffness	6.84 KN/mm
Max load at cavity	32.5 KN

8. Ferrite absorbers

Ferrite absorbers were determined to be the most efficient HOM damping scheme for the five-cell cavity.

Fig. 12. Ferrite absorbers to be used for broad band HOM damping.

The absorbers are attached to the beam pipe at 24 cm diameter in the warm section and are water cooled. These absorbers have been directly incorporated from a Cornell design used in storage rings [6]. Prototype absorbers shown in Fig. 11 were constructed to test HOM damping on the Cu prototype and the measurements confirm the damping of HOMs as predicted by simulations [4]. The actual absorbers have been manufactured by ACCEL and assembled in class 100 clean room. Fig. 12 shows the absorbers being prepared to be shipped to JLAB for final assembly after cavity BCP.

9. Low level RF

As a long term goal, a new fully digital low-level RF (LLRF) system is well underway. The goal of this digital system will be to integrate the LLRF for all the machines at the RHIC accelerator complex. This will include RHIC, AGS, Booster, electron cooler and EBIS (source). The proposed system will be phase locked to the RHIC master oscillator. The system is based on digital IQ fast-feedback for RF amplitude and phase control. The stability targets for the ERL cavity and gun are $<10^{-4}$ in amplitude and
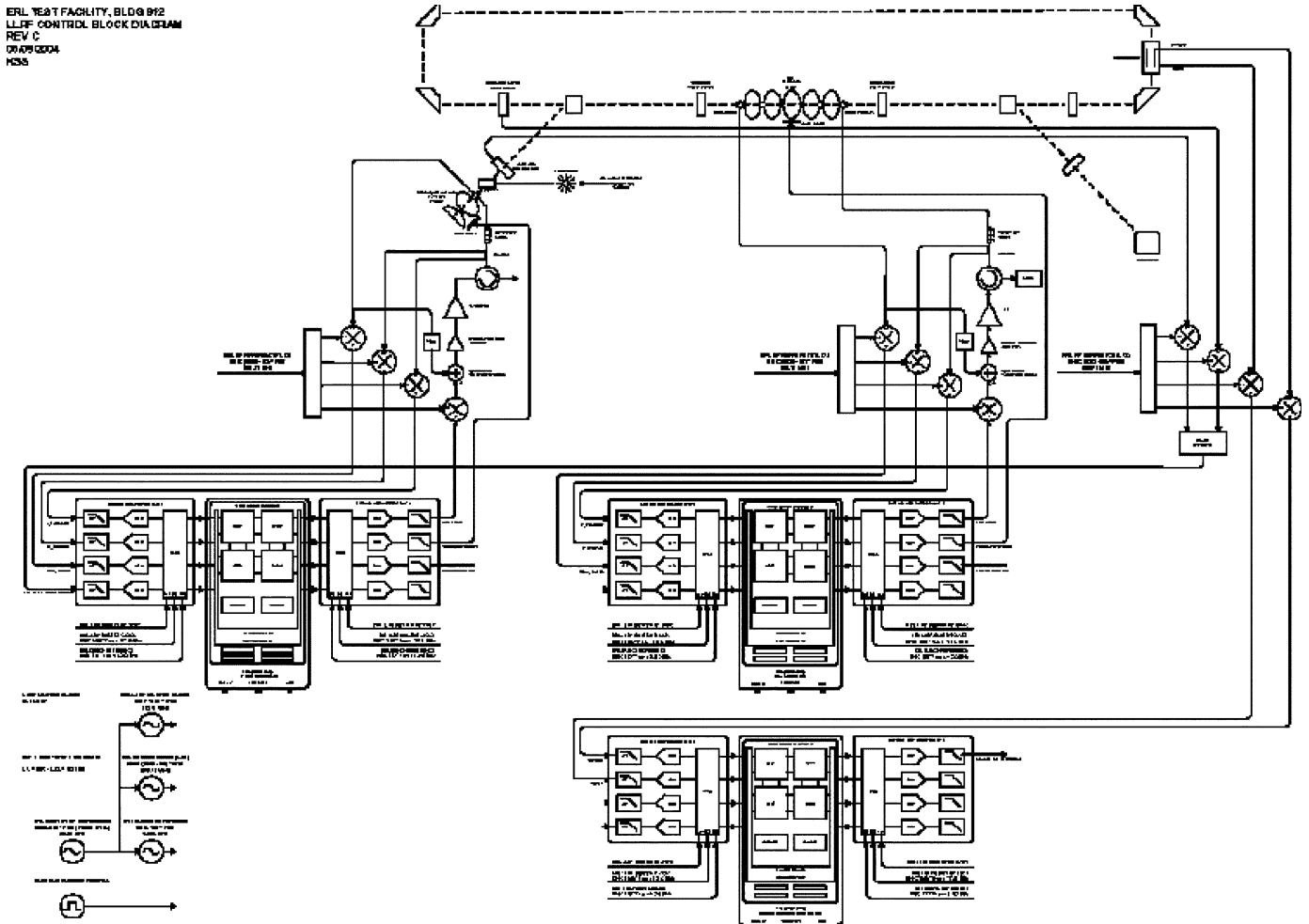

Fig. 13. Block diagram of the LLRF system adapted from SNS RF system to 703.75 MHz.
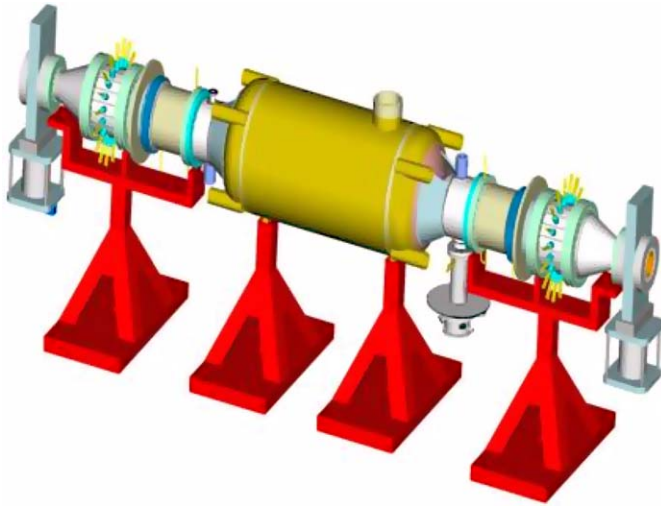
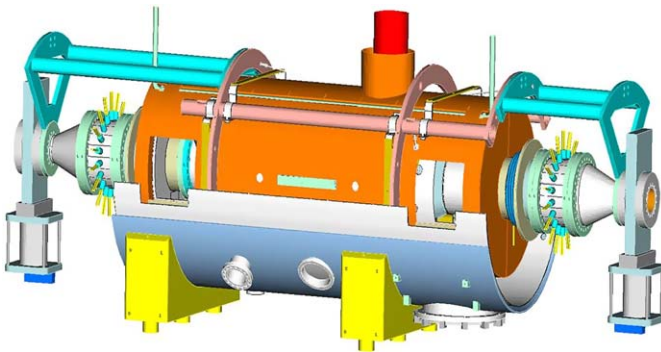Fig. 14. Proposed assembly of the cavity string, FPC, ferrite absorbers, and gate valves at JLAB clean room.

Fig. 15. Cut away view of assembly of cavity cryostat and Helium line at BNL.

$<0.1°$ in phase. The electronics are based on a generic carrier platform with "PowerPC" embedded FEC running VxWorks. The XMC daughter sites for daughter modules (DSP & FPGA signal processing, DAC/DDS, ADC, etc.) implement all control functionalities. A preliminary system based on the SNS RF system adapted to 703.75 MHz is already in place for the cavity testing and as a backup control system is shown in Fig. 13 [7].

10. Cryomodule assembly

Since, the chemical treatment of the cavity is set to take place in JLAB, the assembly of the cryostat is split into two phases. The clean cavity along with the end groups, power coupler, ferrite absorbers, and the gate valves will be assembled in a class 100 clean room at JLAB as shown in Fig. 14. The cavity string attached to the space frame will be transported to BNL to finish the final assembly of the cyrostat components in the beam line. Fig. 15 shows an engineering drawing of the five-cell cavity and cryostat as installed.

11. Summary

A high current superconducting five-cell cavity in an energy-recovery mode was proposed for the electron cooling project at RHIC. The fabrication of the Nb cavity is completed and tuning and chemical treatment of the cavity is anticipated to finish by August 2005. The status of the cavity and cryostat components have been discussed in detail. The superconducting module is anticipated to be finished and installed in December 2005 for cold emission testing for the prototype ERL at BNL.

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